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Combined Neutron and X-ray imaging for non-invasive investigations of cultural heritage objects

D. Mannes[a,*], F. Schmid[a], J. Frey[b], K. Schmidt-Ott[c], E. Lehmann[a]

[a]Neutron Imaging and Activation Group, Paul Scherrer Institut, CH5232 Villigen PSI, Switzerland
[b]Archaeological Service Zug, Zug, Switzerland
[c]Swiss National Museum, Zurich, Switzerland

Abstract

The combined utilization of neutron and X-ray imaging for non-invasive investigations of cultural heritage objects is demonstrated on the example of a short sword found a few years ago in lake Zug, Switzerland. After conservation treatments carried out at the Swiss National Museum the sword was examined at the Paul Scherrer Institut (PSI), Villigen (CH), by means of neutron and X-ray computer tomography (CT). The two types of radiation show different interaction behavior with matter, which makes the two methods complementary. While X-rays show a strong correlation of the attenuation with the atomic number, neutrons demonstrate a high sensitivity for some light elements, such as Hydrogen and thus organic material, while some heavy elements (such as Lead) show high penetrability. The examined object is a composite of metal and organic material, which makes it an ideal example to show the complementarity of the two methods as it features materials, which are rather transparent for one type of radiation, while yielding at the same time high contrast for the other. Only the combination of the two methods made an exhaustive examination of the object possible and allowed to rebuild an accurate replica of the sword.

Keywords: Neutron tomography; X-ray tomography; combined examintation; cultural heritage objects

* Corresponding author. Tel.: +41-56-310-4610; fax: +41-56-310-3131.
E-mail address: david.mannes@psi.ch

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1. Introduction

Cultural heritage objects, which are generally unique and delicate, have to be studied by means of non-invasive testing methods. Among these, techniques based on the transmission of radiation, such as neutron and X-ray imaging have proven to be particularly suitable as they provide inside information on the structure and composition of the studied object (Lehmann et al. (2005); Mannes et al. (2014); Morigi et al. (2010); Rant et al. (2006)). The studied objects most often represent composite materials, which can consist of a large variety of different constituents such as metals, ceramics or organic material (wood, textiles etc.). To this add further substances related to the aging (e.g. corrosion products), conservation treatments (biocides, consolidants etc.) or storage (e.g. moisture). Cultural heritage objects represent thus a very versatile group with respect to the composition as well as on the questions and topics they represent.

With neutron and X-ray imaging two methods are available, e.g. at PSI, which can be used due to their differing and partially complementary attenuation behavior for the investigation of very different problems. While neutrons feature high contrast for hydrogen and thus for organic materials accompanied by good transmittance for most metals, X-rays show high contrasts for metals and good transmittance for materials consisting of light elements. Depending on the composition of the object and the question to be studied either method can be the most appropriate.

In many cases, the utilization of only a single method delivers partial answers, where the combined utilization of neutron and X-ray imaging yields the complete information, although it is still challenging to properly combine the respective attenuation coefficients μ and Σ. These are material parameters describing the attenuation behavior of X-rays (μ) and neutrons (Σ) at a given energy with matter (Chadwick et al. (2006); Hubbell and Selzer (2004)).

With two dedicated neutron imaging installations, one outfitted with an additional X-ray tube, the Paul Scherrer Institut, Switzerland, is well equipped to perform combined X-ray and neutron investigations (Kaestner et al. (2011); Vontobel et al. (*in preparation*)). In this paper we demonstrate the potential of this kind of complementary investigation on the example of a medieval sword found in Lake Zug (Schmidt-Ott et al. (2014)). Only the combination of X-ray and neutron imaging allowed an exhaustive examination yielding full information on the manufacturing process of this special sword type, which resulted eventually in the reproduction of a replica of the sword by means of experimental archaeology (Bernasconi et al. (2014)). Other examples, where the combination of both methods had been used successfully for investigations of cultural heritage objects are described in Deschler-Erb et al. (2004), Lehmann et al. (2010) and Mannes et al. (2014). Also due to the successful combined investigations, a second X-ray setup for high-resolution purposes at the ICON facility will be realized, thus complementing the possible applications and strengthening the flexibility of the facilities.

2. Material and methods

2.1. Material

The object was a short sword, which was found in lake Zug (Switzerland) in 2010. The weapon is a so-called “Swiss degen”, a secondary weapon typical for the end of the 15th century. A detailed report on the weapon and its historic context is given by Frey (2014). After its recovery the well-preserved sword was transferred to the conservatory department of the Swiss National Museum in Affoltern (Switzerland), where it had been subjected to exhaustive conservation treatments, which are described in detail by Schmidt-Ott et al. (2014).

After the conservation and mainly surficial documentation of the object further examinations were requested to get better insight on issues such as the condition and state below the surface, which can’t be directly inspected. Aside from the documentation of the condition, the actual build-up and construction of the hilt was of special interest. Here, parts of the grip and guard consist of pieces of boxwood (Buxus sempervirens), which have been well preserved on the lake ground. Only two other comparable examples of this special type of weapon are known; from these two, one had been modified on several occasions in the past, while for the other one only the metal parts remain, so for none the original construction can be examined. This information is relevant for the proper classification of the weapon. Furthermore it was planned to make an exact copy of the sword by means of experimental archaeology, hence making knowledge on the actual construction of the hilt a necessity.

2.2. Experimental setup

The neutron and X-ray tomography investigations were performed at the neutron imaging facility NEUTRA at the Paul Scherrer Institut, Villigen (Switzerland) (Lehmann et al. (2001)). The beamline is fed with neutrons in the thermal spectrum by the spallation neutron source SINQ (Blau et al. (2009)). The facility is equipped with an optional X-ray source (max. voltage 320 kV), which can be selected as alternative radiation source to neutrons. The X-ray tube can be positioned remotely controlled in-line with the standard neutron setup, which allows directly comparing the resulting images, as the experimental geometry for both radiation sources is highly similar.

The experiments were carried out at the end position of the NEUTRA beamline using a scintillator-digital camera system as detector. The utilised camera was a cooled Andor CCD-camera with 2048 x 2048 pixels looking onto a field of view of 307 x 307 mm2 resulting in a pixel size of ca. 0.15 µm/pixel. For the neutron measurements a 100µm thick 6LiF:ZnS screen was used as scintillator, while a CAWO OG 8 was used for the X-ray investigation.

To ensure a stable positioning of the sword during the tomography the sword blade was inserted in an aluminium tube and fixed with custom made aluminium thread bolts (Fig. 1). The blade and the guard were carefully enwrapped in aluminium foil to avoid damage by direct contact with the sample holder.

The overall length of the object was 61 cm, hence it was larger than the field of view. The actual tomography runs were thus carried out in three height steps to assure that the entire object was covered within the recorded images and to provide comfortable overlapping between the different images. The overlapping was necessary to ensure a gapless reassembled image over the full height. For each height level 625 neutron projections were acquired with an exposure time 20 s. After the neutron tomography the procedure was repeated with X-rays operating the X-ray tube with 150 kV, the exposure time was 4 s.

Fig. 1. (a) The examined short sword in its sample holder consisting of an Aluminium tube; the object was fixed with aluminium thread bolts. (b) and (c) show neutron and X-ray transmission image respectively, each assembled from three individual projection at different heights.

2.3. Data processing and evaluation

The neutron and X-ray tomography data of each level were reconstructed using the reconstruction software *Octopus*®. Characteristic features in the overlapping areas of the resulting data sets were used to align and position the data before merging. The overlapping areas were subsequently reassembled by interpolation of the voxels. As result, two tomography data sets, one neutron and one X-ray tomography data set, of the entire sword were obtained. Further evaluation and visualization of these data sets was carried out using the software *VG studio max*. As the acquisition conditions of the two data sets was almost similar, only small adjustments on the spatial scaling (<1%) were necessary for matching the neutron and X-ray data.

3. Results

The data sets acquired with the two radiation types show complementarity to a high extent as should be expected for an object consisting of metal and organic material. When comparing the transmission images in Fig. 1 (b) and (c) the differences become already apparent. While the organic material, i.e. the wooden parts of the hilt, yield a very high contrast in the neutron image it is barely visible in the X-ray image. The metal parts on the other hand, such as the blade or the pommel show much higher transparency in the neutron image, while they give high contrast for X-rays. The metallic ornaments in the hilt are only visible here, but can't be found in the neutron projections, where their signal drowns in that of the wooden parts.

The reconstructed slices confirm the impression of complementarity. While the wood and its structure are visible in the neutron CT slices smaller metallic parts such as the ornaments are barely visible (Fig. 2 c and d). Larger metal pieces, such as the tang, the central metal piece of the hilt, as well as the metal pins connecting grip and guard to prevent rotation of the hilt are visible. In the X-ray CT slices the metal parts appear so dominant entailing a lot of strong reconstruction artifacts that the wooden structure cannot be made out in the images. Here, the signal from the metal outshines the signal from the organic parts. Nevertheless, the distribution and position of the small metallic ornaments can solely be determined with help of the X-ray data.

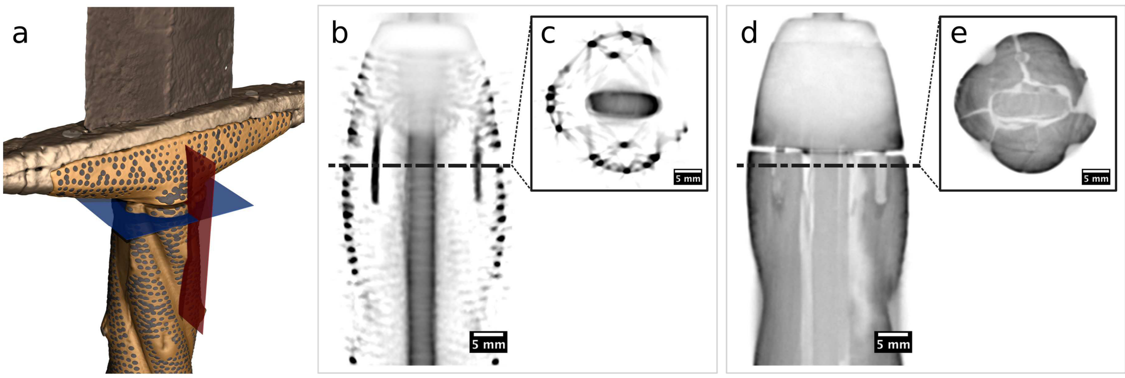

Fig. 2. (a) shows a rendered 3D view of the combined CT-data sets indicating the position of the slices: (b) and (d) vertical plane, (c) and (e) horizontal plane. (b) and (c) show slices with inverted grey scale through the X-ray, (d) and (e) neutron tomography data sets of the sword; The X-ray slices show all the metallic parts including the ornamental inlays on the surface; the neutron slices show the wood structure as well as the main metal parts.

The wooden grip on the other hand can only be examined with help of the neutron data as no structure can be made out in the X-ray data. The neutron CT-data allows to examine for example the wood structure itself. The grip of the sword shows some larger decorative nails, which have been driven in what appears to be small elevations corresponding to small knots in the wood. The high regularity in the distribution of these knots already suggests that they are not all naturally grown. This impression is confirmed, when looking at slices through the data set along the nails (Fig. 3). With exception of one nail, which had been driven into a naturally grown knot, all other nails are placed in fake knots, which had only been carved into the wooden grip for aesthetical and symmetry reasons. Overall there are only three larger knots with the used piece of boxwood, while 16 larger decorative nails had been inserted in the grip.

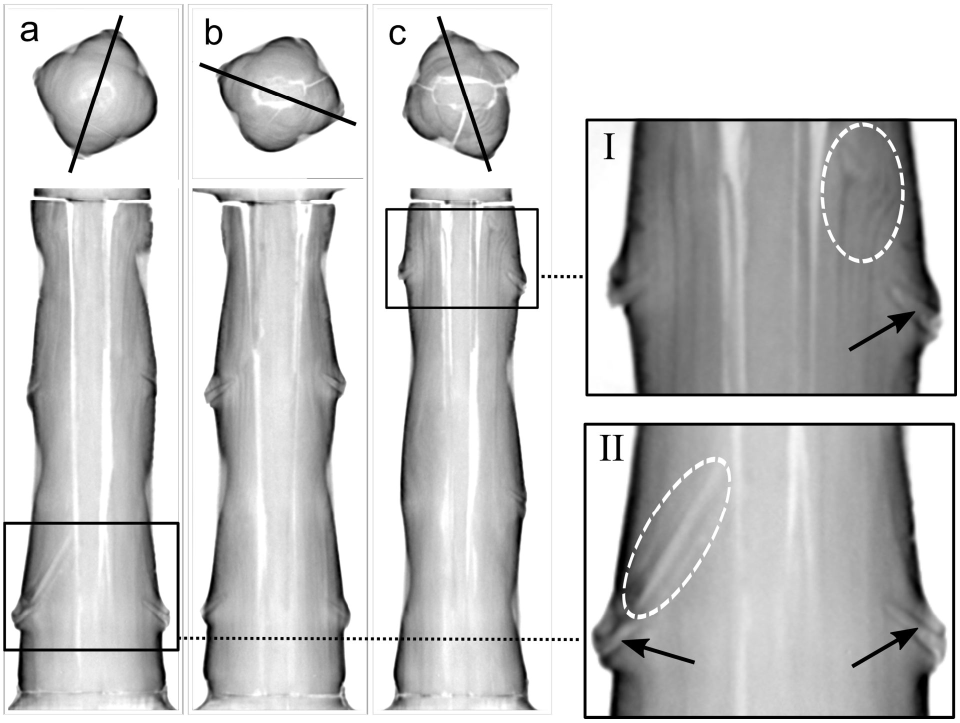

Fig. 3. Inverted slices through the neutron CT data set. The lines in the small horizontal slices on top indicate the section plane of the corresponding larger slice below. The region surrounded by the dashed white line in the boxes I and II mark the knots, the arrows mark larger nails. In box II the only nail in a knot can be seen; all other nails are not closer to a knot than seen in box I.

The neutron CT data yields still more information on the organic parts of the sword hilt. In Fig. 2 (d), a view perpendicular to the sword axis, thin material layers are visible between the central metal part of the sword hilt and the wood part of the grip. Fig. 4 (b) shows a slice following a custom path through the data set along the thin material layers. These reveal to be thin strands of wood, which had been inserted in the small gap between metal and wood to prevent wobbling of the grip and assuring a steady hold. On the one side of the metal two smaller strands have been inserted, while on the other side one long strand had been used. The slices imply that the strands, which seem all to come from the same board, are made of a different wood species with large annual rings and strong contrasts between early and late wood, such as Norway spruce (Picea abies) or white fir (Abies alba).

The pommel concludes the hilt and consists of different parts (Fig. 5). The most prominent is the cap, which consists of a metal sheet shaped into a pyramid with hexagonal base area. The metal cap is fixed to the tang with a rivet and incloses a small wooden disk and the end of the wooden grip. The wooden disk is only visible in the neutron images (a) and (b), while it can't be found in the corresponding X-ray slices (d) and (e). Here, again the ornamental metal inlays are visible as well as two pins fixing the wooden disk to the grip, preventing rotation. In the wooden disk small annual rings without noticeable curvature are visible; the small curvature indicates, that the wood was taken from a tree with a large diameter, suggesting that a different species was used than for the rest of the grip as box tree individuals normally only reach a maximum height between 8 and 10 m and a diameter <50 cm. The horizontal slice to (c) and (f) indicate that the tang in the centre of the pommel as well as the inside of the metal cap show signs of corrosion. The corroded areas are visible as areas lower attenuation and hence lower density in the X-ray images. These are visible surrounding the tang in the centre but as well on several areas on the enveloping meal cap. In the neutron images the areas appear quiet differently; here, some areas show higher other areas lower attenuation than the centre of the metal tang. This indicates that several areas with different levels or phases of corrosion are present, differing in their hydrogen content and density.

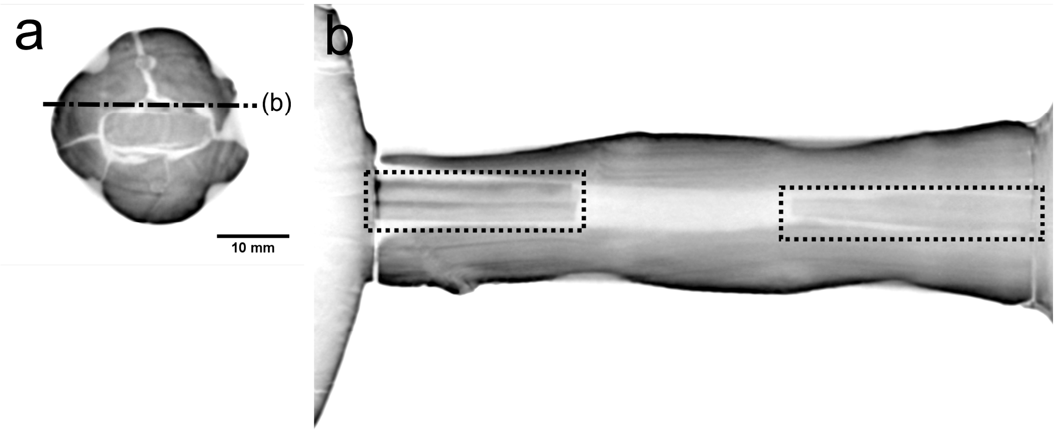

Fig. 4. (a) horizontal slice through neutron CT-data set; the lines indicate the position of the vertical slice (b); the dashed boxes point at thin strands of wood inserted between metal and wood to prevent wobbling of the grip.

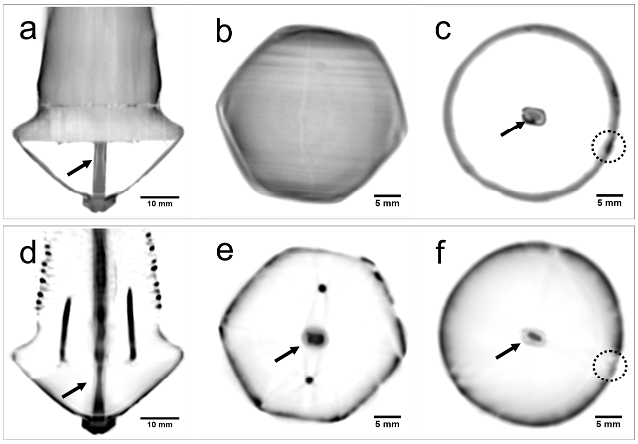

Fig. 5. Inverted slices through the neutron (a – c) and X-ray (d – e) tomography data set; (a) and (d) show vertical (b) – (c) and (e) – (f) respectively show vertical slices through the pommel of the sword; (a) and (b) show a small wood disk insight the pommel; (d) and (e) the pins which are used to fix this disk. Grey scale variations in the central part (tang) (arrows) and outer cap (dotted circle) indicate corroded areas visible as areas of low density in the X-ray images and with high attenuation (high H-concentration) in the neutron images..

Fig. 6. 3D-visualisation of the combined X-ray and neutron CT data sets; information of the small metal pieces such as ornaments pins and nails originate from the X-ray CT; the wooden parts and larger metal parts originate from the neutron CT

The individual data sets acquired either with neutrons or with X-ray only provide information from a viewing points. Only if a synthesis of the two data sets is made, the full information is made available as can be seen in Fig. 6. Here, the neutron and X-ray CT data sets are combined by 3D-visualisation software. Only this fusion of the two data sets yields a holistic virtual model of the sword. Information on the organic parts as well as on the larger metal parts such as the blade or the guard are yielded by the neutron data, the former because of the higher contrast the latter because of the higher transparency compared to X-ray. Information on the smaller metal parts originates from the X-ray CT as these parts could not be clearly determined in the neutron data. Thus, using both methods every material can be visualized allowing to virtually disassemble the sword in all its components and hence to comprehend how the sword was manufactured.

4. Summary

Neutron and X-ray tomography was used to examine a short sword, classified as “Swiss degen”. Each method for itself yields only a fragmentary image of the object: in the X-ray data the organic parts are not or barely visible. Only the metal parts especially the small metallic ornaments of the hilt can clearly be distinguished. In the neutron data set these smaller metal pieces cannot or scarcely be seen in the tomograms. Here, the organic parts such as the wooden grip and wooden part of the guard as well as a wooden disc concealed by the metal cap of the pommel yield the highest contrasts. Only the examination with both methods provides the full information and only the combination of the two methods yields a holistic perception of the object.

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